LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-CONF-486041

A Time Projection Chamber for High Resolution Fast Neutron Imaging of Missile Warheads

N. Bowden, G. Carosi, M. Heffner, C. Roecker, I. Jovanovic

June 9, 2011

INMM Annual Meeting
Palm Desert, CA, United States
July 17, 2011 through July 21, 2011

A Time Projection Chamber for High Resolution Fast Neutron Imaging of Missile Warheads

N. S. Bowden[a], G. Carosi[a], M. Heffner[a], C. Roecker[b], and I. Jovanovic[c]
[a]*Lawrence Livermore National Laboratory, Livermore, CA 94550 USA*
[b]*School of Nuclear Engineering, Purdue University, West Lafayette, IN 47907 USA*
[c]*Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, USA*

1 Introduction

Future strategic arms control treaties may require verification of the number of warheads installed upon a missile. Inspections supporting such verification will likely be subject to many constraints. One of these is that a measurement should not reveal classified warhead information. In addition, a highly desirable feature would be the ability to determine, within a single measurement, the warhead count of a missile at several meters standoff. Fast neutron imaging appears to be especially attractive for this arms-control application. Unlike gamma rays, fast neutrons emitted by a warhead have little potential to reveal detailed information about the composition of the source, and they can easily penetrate the warhead and surrounding material.

Here we describe a technology that could provide very high intrinsic fast neutron imaging resolution, possibly allowing warhead counting measurements with a minimum of post-processing – a desirable feature for confidence building and transparency. Time Projection Chambers (TPCs), which have been widely used in particle and nuclear physics research for several decades, provide a convenient means of measuring the full 3D trajectory, specific ionization (i.e particle ID) and energy of charged particles. For this application, observation of two recoil protons from a double fast neutron scatter on protons in hydrogen or methane gas provides a complete kinematic constraint upon the direction and energy of the incoming neutron. Intrinsic angular resolution of few degrees can be achieved by this technique, prior to any mathematical inversion or maximum likelihood imaging technique.

This double scatter imaging mode has been demonstrated using a laboratory prototype device, despite the fact that it was entirely un-optimized for this application. We will describe these results, and present a device design well suited to warhead counting for treaty verification applications.

2 Time Projection Chambers

TPCs comprise a gas filled interaction region, a two dimensional charge collection surface and some form of electron gain located just in front of the charge collection surface to improve the signal to noise. For this application, a hydrogen bearing gas is chosen – when an incoming neutron scatter produces a recoil proton, the ionization produced as the proton slows is drifted to the readout surface. The combination of the two dimensional charge collection information with the charge arrival time yields the 3D ionization profile of the recoiling particle (Figure 1). This is a particular advantage of

TPCs for SNM imaging – the ability to record particle specific ionization. This means that efficient particle identification is available, allowing strong rejection of gamma-ray backgrounds.

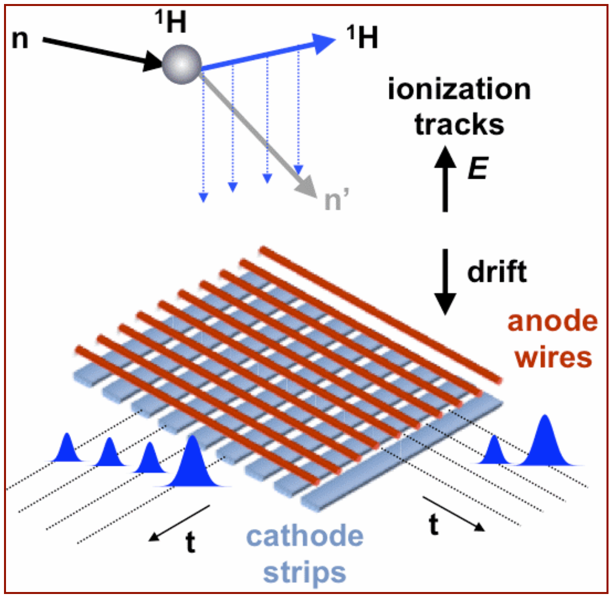

Figure 1
Representation of TPC operation using, in this example, a crossed wire/strip readout.

We have examined the use of hydrogen bearing TPCs using two distinct modes. Most often, an incident neutron will scatter only once off a proton within the TPC. Since the scattered neutron carries unknown momentum, incomplete directional information is obtained. However, the recoil proton angular distribution peaks at the angle identical to that of the incident neutron. When averaged over even a few tens of events, the resulting recoil proton directional distribution captures information about the location of neutron sources present. Less frequently, an incident neutron can scatter off two protons. Observing both of those protons provides a complete constraint upon the incident neutron energy and direction. Although this mode is somewhat less efficient, a direct imaging of the neutron sources present can be obtained by this technique. No other fast neutron imaging technique can build a direct, high resolution image of the "scene" in this way.

3 Detector Description

The laboratory prototype neutron TPC (nTPC) consists of a 44 cm-diameter, 66-cm long pressure vessel, which contains the detector gas, drift field cage, amplification region, and the 2D readout plane consisting of 128 anode wires and 64 cathode strips (Figure 2). Low event multiplicity allows the use of a cost-effective readout system employing independent readouts for cathode and anode planes, resulting in a total of 192 channels. The outer pressure vessel is made from standard stainless steel components and allows a maximum operational pressure of 10 bar(a). The entire assembly weighs approximately 0.5 ton, although for this lab prototype no effort was expended to design the vessel to a fieldable weight. A detailed description of the device and results from it using the single-scatter mode can be found in [1].

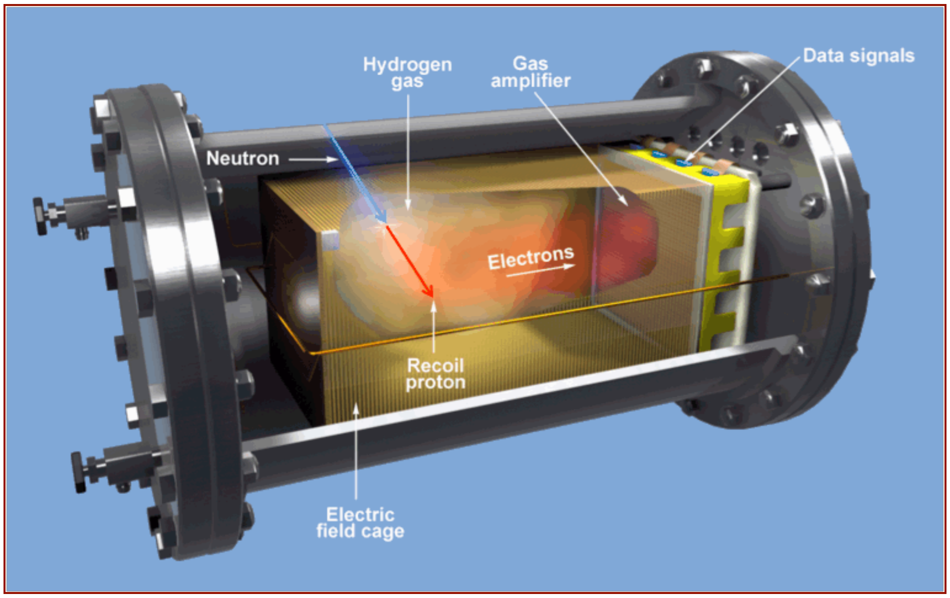

Figure 2
Detector vessel and field cage assembly

4 Data Analysis

We have developed reconstruction software that consists of a data parser, hit finder, tracking algorithm, and an ionization profiler. Due to the use of two orthogonal detector readout planes, we use the time correlation between those two planes to identify 3-dimensional hit locations. This use of time coincidence also represents a powerful method for electronic noise rejection. The list of 3-dimensional hits is subsequently projected back into two planes, allowing the use of two independent tracking algorithms.

The tracking algorithm is based on a combination of a standard Hough transform algorithm with a least squares linear fit. The Hough transform algorithm is used initially to obtain the directions of the projections of the particle track in two detector planes, since this transform is a robust means of finding a track in data sets which might contain events that lie off of a track. Hits that lie on the track found by the Hough transform are identified, and the track angle is then found with greater precision by employing a least squares fit (Figure 3a). The amplitudes of the hits found along the reconstructed track are used to form an ionization profile that is then used for particle identification purposes. An example ionization profile is shown in Figure 3; one can clearly see the expected features of the ionization profile, e.g. the Bragg peak at the end of the particle track.

For the double scatter mode, we select events that contain two tracks identified as proton recoils. After checking that the kinematics of those two tracks are consistent with the multiple scattering of a single incident neutron, the incident neutron direction and energy is found via simple vector momentum addition.

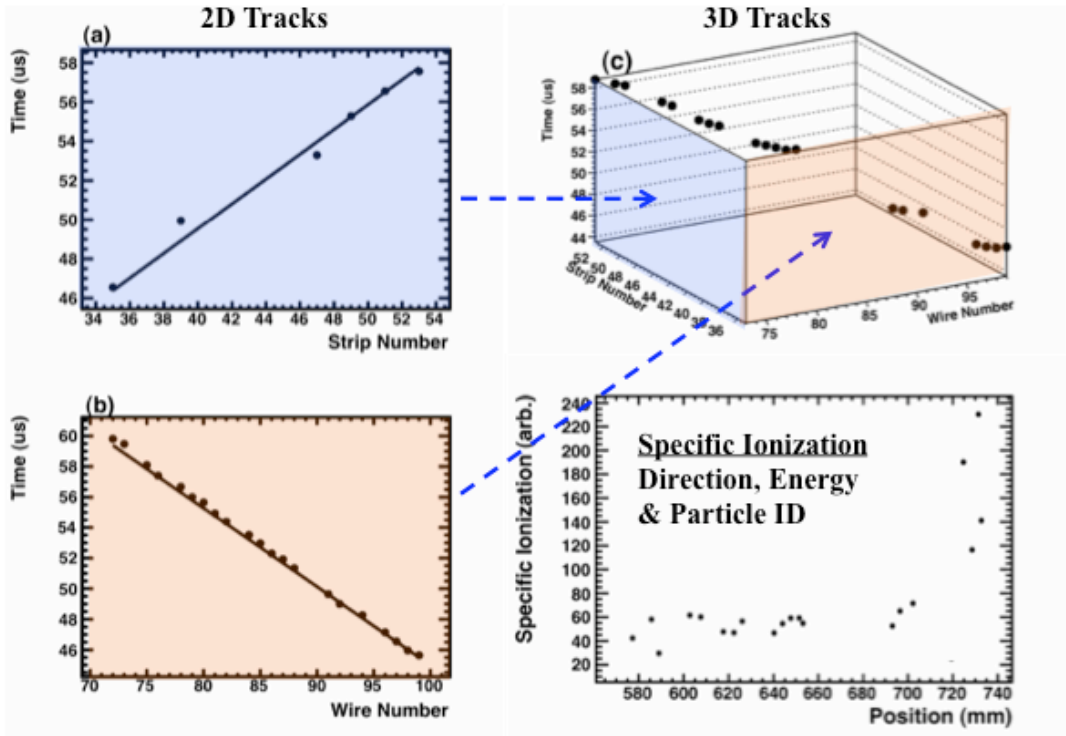

Figure 3
A pictorial representation of the tracking analysis. Tracks observed in each of the 2D readout planes are formed into 3D track via their time correlation. In addition to the 3D trajectory of the particle, the specific ionization along the track is also determined. This provides particle identification as well as breaking the directional degeneracy along the track axis.

5 Results

The vast majority of events recorded by the nTPC involve an incident neutron scattering off a single proton (a “single scatter” event). Although an individual single scatter event does not provide enough information to directly point back the neutron source, the recoil proton direction and energy can be used to form a probability distribution function (PDF) of the possible directions from which the neutron could have arrived, and the relative likelihood of each direction.

We sum the PDFs of individual events into a cumulative PDF. For the search application for which the prototype nTPC was optimized, the mean position of this cumulative distribution provides a robust, rapid and accurate indication of neutron source position. On first inspection, it is less well-suited to this multiple source counting application, due to its broad width. Examples of the resulting cumulative PDFs at shown for three neutron source positions in Figure 4. For this reason, we have adopted a template matching analysis for the single scatter dataset.

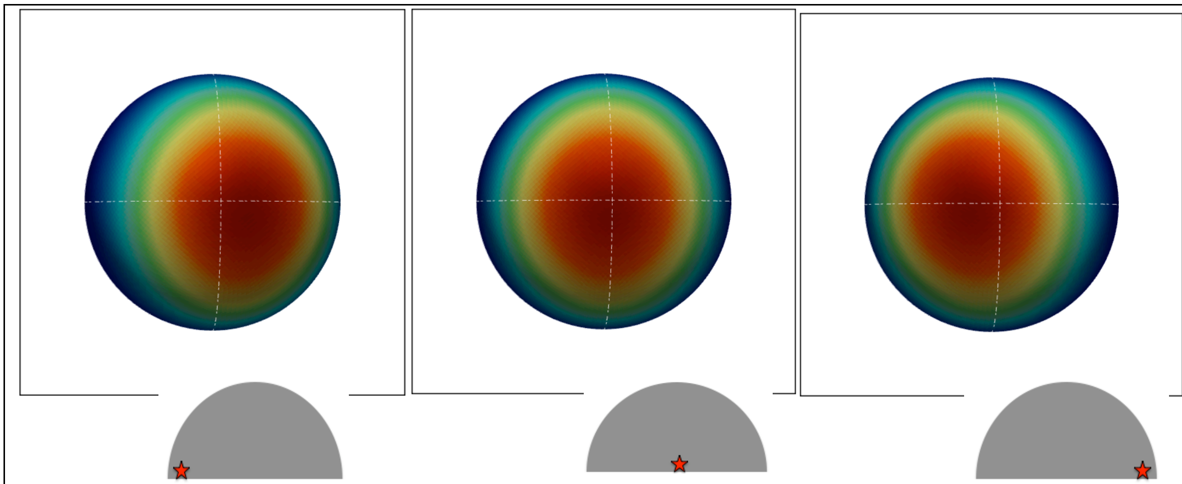

Figure 4
PDFs for three single source configurations (including pictorial representations of those configurations).

The shape of the cumulative PDF contains sufficient information to be able to discriminate among different source configurations at 3-5 meter standoff. This is demonstrated here via a template matching technique. Such an approach can be advantageous where a treaty counterparty wishes to divulge as little information as possible, while still providing a means to allow verification. In this context, the broad, relatively featureless, cumulative PDF is ideal – casual observation of the distribution reveals little, but careful comparison against a suite of templates can provide verification that the scene conforms to an expectation.

To perform this analysis we acquired a suite of “templates” (cumulative PDFs) comprising many different “scenes” (neutron source configurations). In addition we acquired many “observations” of several of those scenes. Each observation was compared to every template via the calculation of a “test statistic”, whose value would be zero if the scene and template were identical, i.e. if they matched, and would become larger the more the two differ.

The ability of the nTPC to correctly identify the template corresponding to each observation as a function of the observation time is shown in Figure 5a. Here we compare the observations to all templates, and check whether the template with lowest test statistic value does in fact match the observation scene. The suite of templates includes each scene at both 3m and 5m standoff – we make no assumption about prior knowledge of the standoff, except that templates exist for all possibilities. The ability to correctly identify the scene improves considerably at an observation time of 60min, but does not reach 100%.

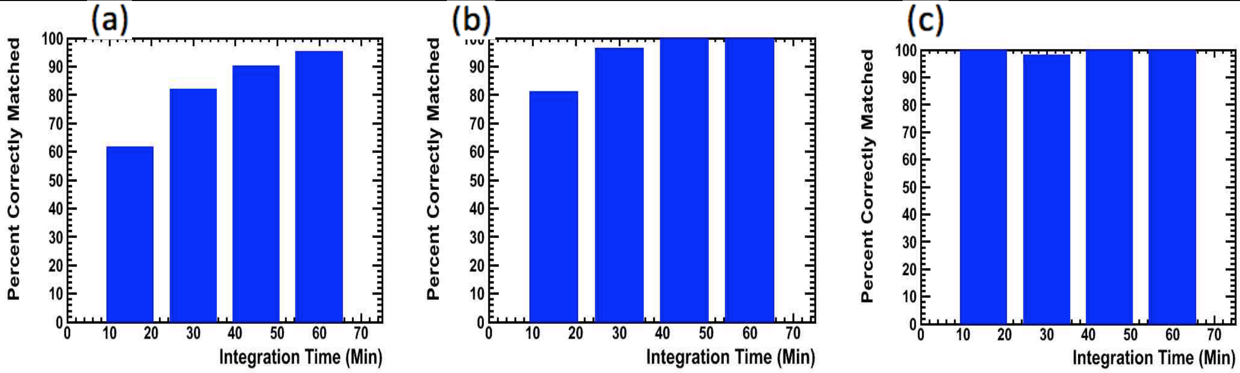

Figure 5. (a) Percent of combined 3m and 5m observations that correctly matched the correct template (the same scene and standoff distance). One can clearly see that template discrimination greatly improves with integration time. (b) Percent of correctly matched observations for 3m observations & templates. (c) With the inclusion of rate information 3m observations are matched to their correct 3m template almost 100% of the time even at 15 minutes.

The situation improves dramatically if one assumes knowledge of the standoff distance, e.g. if one compares 3m observations to a suite of templates comprising only those acquired at a 3m standoff. Figure 8b shows how the success rate of correctly matched templates rises to 100% for observation times of 45 min to 1 hour, once a known standoff is assumed. Finally, the results presented above only used the shape for each template – each PDF, be it an observation or a template, was normalized to the same integral value. One can easily incorporate the neutron detection rate information by simply multiplying each observation/template by its respective neutron count rate. When included with the assumption of a particular standoff distance we achieve almost 100% template matching efficiency for even just 15 minutes of integration time (Figure 5c). Only 1 half-hour observation out of 57 half-hour observations chose the incorrect template.

Due to the very low efficiency with which the prototype nTPC is able to record the full tracks of double scatter events, this dataset has limited statistics. We stress that this is not a general feature of this measurement technique, but rather represents the use of a device that is decidedly non-optimal for it. Nonetheless, we believe that we have been able to perform a proof of principle demonstration of this high resolution measurement mode. As demonstrated in Figure 6, we are able to identify events within our dataset that are due to neutron double scatters. As expected for this hardware configuration, an angular resolution of about 10^{o} was achieved in this measurement.

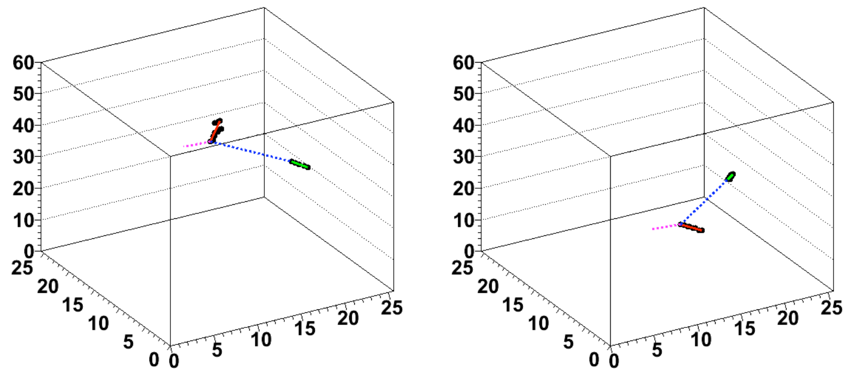

Figure 6. A selection of Double Scatter events, due to a single neutron source. The dashed pink and blue lines represent the inferred paths of the incident and scattered neutron, respectively. Although it may not be apparent from the angle at which these events are viewed, each satisfies the kinematic constraints of a double scatter, as described in the text. The red and green lines are the first and second scattered proton tracks, respectively. The plot axes represent position within the TPC, measured in cm.

6 Optimized Design Concept and Safety Considerations

Based upon extensive simulation work, we have developed a deign concept for a device optimized for high resolution imaging of warheads. Use of methane gas, which has a higher number of hydrogen atoms per molecule, would allow for efficient unpressurized operation. A larger volume of 250 liters would also provide reasonable efficiency for double scatter events, while not requiring a large number of readout channels. We predict that such a device would be able to directly resolve warheads at 10m standoff in approximately 1hr of observation time.

This technology inherently requires the use of a counting gas that contains a substantial fraction of hydrogen. We have had considerable experience using such gases, and find that with careful design and well thought out operating procedures they presents no safety risk. Nonetheless, this is a topic that requires considerable engagement with potential end-users. Methane appears to be particularly attractive as a target gas, since it has high hydrogen content, is inexpensive and is commonly transported in commerce (e.g. canisters for portable gas stoves). Methane has other desirable features. Its Lower Flammability Limit (LFL) is relatively high at 5%; that is, an air/methane mixture must be at least 5% methane to be flammable. Complete release of $0.25m^3$ of methane mixed into a room larger than $5m^3$ cannot result in a flammable mixture. Similarly, its Upper Flammability Limit (UFL) is 15%, meaning that there is only a narrow range of air/methane mixtures that are flammable. Finally, the energy released by the combustion of $0.25m^3$ of methane in air is less than that by the combustion of 1 liter of standard liquid scintillator. All other fast neutron imaging technologies using liquid scintillator will use liquid volumes substantially greater than this.

An unpressurized system is clearly desirable from both a practical and safety point of view. The gas envelope could be lightweight, and there is no possibility of the sudden release of the counting gas. Any puncture in the gas envelope would only result in the slow diffusion of the counting gas into the surrounding environment.

7 Conclusion

Here we have performed exercises with the Neutron TPC in order to determine its ability to resolve multiple closely spaced fission neutron sources – a task that may be relevant to future treaty verification activities. Although the current implementation of this technology was developed with different goals in mind, the results from both the neutron imaging modes supported by this technology show promise. The low resolution mode, in which a single neutron scatter is detected, when analyzed via a template matching technique can clearly distinguish between a wide variety of neutron source configurations. This is particularly true when neutron detection rate information is also included in the analysis. Such an approach may be attractive where a treaty counterparty requires that measurements do not reveal the actual source configuration, but where it is necessary to verify that a configuration matches an agreed template.

We have also demonstrated a measurement mode with much higher angular resolution – tracking two recoil protons set in motion by the same fast neutron. The small active volume of our prototype device resulted in a very low efficiency for these double scatter events occurring. This was expected, given that the device was in no way optimized for this more stringent measurement. Nonetheless, we were able to collect a limited double scatter dataset, with an angular resolution of approximately 10°. This performance is consistent with that expected, giving us confidence in our estimates that an optimized device could achieve a higher 3° resolution, with reasonable efficiency.

References

[1] "Directional fast neutron detection using a time projection chamber" N.S. Bowden, M. Heffner, G. Carosi, D. Carter, P. O'Malley, J. Mintz, M. Foxe, I. Jovanovic, Nucl. Instrum. Meth. A, 624 (2010) 153-161.

Acknowledgements

This research is supported by the U.S. Department of Energy National Nuclear Security Administration Office of Nonproliferation and Verification Research and Development.

LLNL-CONF-486041

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.